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Low-mass muscle actuators using electroactive polymers (EAP)

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ABSTRACT

NASA is seeking to reduce the mass, size, consumed power, and cost of the instrumentation used in its future missions. An important element of many instruments and devices is the actuation mechanism and electroactive polymers offer an effective alternative to current actuators. In this study, two families of electroactive polymer (EAP) materials were investigated, including bending ionomers and longitudinal electrostatically driven elastomers. These materials were demonstrated to effectively actuate manipulation devices and their performance is being enhanced in this on-going study. The recent observations are reported in this paper, which also include cryovac tests at conditions that simulate Mars environment. Tests at T=-140°C and P~1 Torr, which are below Mars conditions, showed that the bending actuator was still responding with a measurable actuation displacement. Analysis of the electrical characteristics of the ionomer showed that it is a current driven material rather than voltage driven. Measurements of transient currents in response to a voltage step shows a time constant on the order of few seconds with a response speed that is enhanced with the decrease in drive voltage. The ionomer main limitation is its requirement for being continuously moist. Tests showed that while the performance degrades as the material becomes dry, its AC impedance increases, reaching an order of magnitude higher than the wet ionomer. This response provides a gauging indication of the material wetness status. Methods of forming the equivalent of a skin to protect the moisture content of the ionomer are being sought and a limited success was observed using thick platinum electroding as well as when using polymeric coating.

Keywords: Miniature Robotics, Electroactive Polymers, Hand Simulation, Electroactive Actuators, EAP Materials

1. INTRODUCTION

NASA missions are faced with growing constraints of mass, power, volume and cost with the need to perform increasing number of tasks and experiments. Inexpensive, low-mass, low-power consuming actuators can be used to effectively address these constraints. Examples of space mechanisms and devices that require actuators include robotic arms, miniature rovers, release mechanisms, positioning devices, aperture opening and closing devices, and real-time compensation for thermal expansion in space structures, etc. Actuation materials are finding increasing use to drive mechanisms, where electroceramics (piezoelectric and electrostrictive) and shape memory alloys (SMAs) are the leading alternatives. Examples include the use of electrostrictive actuators for the correction of the aberrations on the Hubble Telescope using the WF/PC II module. Electroactive ceramics (EAC) offer effective, compact, actuation materials and they are incorporated into such mechanisms as ultrasonic motors, inchworms, translators and manipulators. In contrast to electroceramics, electroactive polymers (EAP) are emerging as new actuation materials [Furukawa and Wen, 1984] with displacement capabilities that cannot be matched by the striction-limited and rigid ceramics. A comparison between EAP, EAC and SMA is given in Table 1, and as can be seen from the table, EAPs are lighter and their striction level capability can be as high as two orders of magnitude more than EAC [Bar-Cohen, Xue, et al, 1997]. The mass producability of polymers and the fact that EAPs do not require poling (in contrast to piezoelectric materials) help to produce them at low cost. EAPs can be easily formed in various shapes and can be used to build micro-electro-mechanical systems (MEMS), including both actuators and sensors. They can be designed to emulate the operation of biological muscles [Hunter and Lafontaine, 1992; Shahinpoor, 1994; and Kornblush, et al, 1995] with unique characteristics of high toughness, large actuation strain constant and inherent vibration damping. Further, their response speed is significantly higher than Shape Memory Alloys (SMAs) and their fatigue characteristics is superior to SMAs, which have fatigue life limit of about 1000 cycles when actuated at displacement strain of about 8%. The authors' current study is directed towards developing effective EAPs and taking advantage of polymers' resilience and the ability to engineer their properties.

The development of EAP actuators is involved with an interdisciplinary efforts using expertise in materials science, chemistry, electronics, and robotics. At the initial phase of the authors' study, efforts were made to identify electroactive polymers that induce large actuation strains. Two categories of EAPs were identified including (a) bending actuators: ion exchange membrane platinum composites, so-called ionomers; and (b) longitudinal actuators: electrostatically activated EAPs. These two EAP categories offer the capability to bend or stretch/extend, which

essentially emulate the operation of biological muscles and limbs. In the second phase, efforts were made to identify robotic and planetary applications and demonstrate the EAP actuators capability. A series of mechanisms that include actuators of robotic arm components (lifter and gripper) as well as a surface wiper were developed. Current efforts are concentrated on determining EAPs capability to operate at space conditions of low temperatures and vacuum and encouraging results will be reported herein. In parallel, studies are taking place to determine the capability to control and obtain feedback using EAP actuators in order to produce miniature robotic devices with servo-control capability.

TABLE 1: Comparison of the properties of EAP, SMA and EAC

Property	Electroactive polymers (EAP)	Electroactive Ceramics (EAC)	Shape memory alloys (SMA)
Actuation strain	>10%	0.1 - 0.3 %	<8%*
Force (MPa)	0.1 - 3	30-40	about 700
Reaction speed	μsec to sec	μsec to sec	sec to min
Density	1- 2.5 g/cc	6-8 g/cc	5 - 6 g/cc
Drive voltage	2-7V/10-100V/μm	50 - 800 V	NA
Consumed Power	m-watts	watts	Watts
Fracture toughness	resilient, elastic	fragile	Elastic

* Note: The fatigue life at this level of strain is very short.

2. IONOMERS AS BENDING EAP ACTUATORS

The bending EAP actuator is composed of perfluorinated ion exchange membrane platinum composite (IMPC), where platinum electrodes are deposited on both sides. The actuator is based on a processed Nafion film having the following chemical formula,

$$[-(CF_2\text{-}CF_2)_n\text{-}CF\text{-}CF_2\text{-}]_m$$
$$|$$
$$O\text{-}CF\text{-}CF_2\text{-}O\text{-}CF_2\text{-}SO_3\text{-}M$$
$$|$$
$$CF_3$$

where $n \sim 6.5$, $100 < m < 1000$, and M^+ is the counter ion (H^+, Li^+ or Na^+). The structure and properties of the IMPC have been the subject of numerous investigations (see for example [Heitner-Wirguin, 1996]). One of the interesting properties of this material is its ability to absorb large amounts of polar solvents, i.e. water. In order to chemically electrode the IMPC, platinum (Pt) metal ions are dispersed throughout the hydrophilic regions of the polymer, and are subsequently reduced to the corresponding zero valent metal atoms. This results-in the formation of a dendritic type electrodes. A scanning electron micrographic tests show [Bar-Cohen, et al, 1997] that the Pt metal covers each surface of the film with some of the metal penetrating the subsurface regions of the material. When equilibrated with aqueous solutions the ionomer membrane is swollen to absorb certain amount of water. Swelling equilibrium results from the balance between the elastic forces of the polymeric matrix and the water affinity to the fixed ion-exchanging sites and the moving counter ions. The water content depends on the hydrophilic properties of the ionic species inside the membrane and also on the electrolyte concentration of the external solution.

After 0.18-mm thickness IMPC films are formed they are cut to strips that are 25.0x3.5-mm in size and weighing 0.1-g. To maintain the actuation capability of IMPC, the material needs to be kept moist continuously and providing the necessary ions that are responsible for the actuation. It is interesting to point out that testing the ionomer response in water at 2-V and 1-Hz the IMPC cyclically continued at a relatively constant bending amplitude over a million cycles. Efforts are currently being made to protect the moisture content and some success was observed when using thick platinum electrodes and limiting the voltage to <2-V rather than the levels of 3-5 volts. Using such electrodes, an IMPC film was demonstrated to operate continuously for more than several hours. In addition to the use of thick platinum, efforts are made to form a coating seal using encapsulation methods as a quasi-skin to protect the moisture inside the IMPC films. To enhance the force actuation capability of IMPCs, techniques of producing thicker films as well as modification of the ionomer processing were investigated. Using twice thicker Nafion (#120 Dupont product) to

produce bending ionomer actuators led to an actuation force that is more than 20% higher than the original Nafion (#117). To better understand the actuation mechanism in ionomers the phenomena is studied and modeled. Also, alternative ionomer actuators are being searched.

In addition to the use of thick platinum electrodes, efforts have been made to coat the IMPCs with a polymeric material to retain the moisture levels inside the film. Due to the fluorinated structure of the base Nafion® film, the application and adhesion of a coating to the IMPC is rather difficult. The perfluorinated backbone, the Nafion® film has characteristics similar to that of Teflon® (PTFE) in which adhesion to the surface is negligible. Attempts to coat the IMPC without a surface treatment resulted in coating that was easily removed. To improve adhesion to the IMPC, a chemical etchant (Tetra-etch®) was employed. Initially, the etchant works by removing the fluorine atoms from the surface chains leaving the carbon atoms in the polymer backbone temporarily electron deficient. Then, the etched surface is exposed to moist air, which results in the formation of a monolayer functionalized polymer backbone containing e.g. hydroxyl, carbonyl, and carboxyl groups, and therefore enabling adhesion. Tests of the performance of an etched IMPC did not show any noticeable loss in actuation response. A low modulus polysilicon coating (Dow Corning® 92-009 Dispersion Coating) was applied to the surface of the etched IMPC electrode and it exhibited improved adhesion as compared to the untreated IMPC. Initial results have shown that the coated IMPC operated continuously for approximately 24 hours under ambient conditions. Further attempts to improve and evaluate coated the IMPC actuators are ongoing.

When an external voltage is applied on an IMPC film, it causes bending towards the anode at a level that increases with the voltage. The displacement actuation reaches saturation as the voltage rises (see Figure 1). Under an AC voltage, the film undergoes swinging movement and the displacement level depends not only on the voltage magnitude but also on the frequency. Generally, activation at lower frequencies (down to 0.1 or 0.01 Hz) induces higher displacement and it reaches saturation as the voltage increases. The movement of the actuator is controlled by the applied electrical source but it is strongly affected by the water content that serves as an ion transport medium. The ionomer respond to the drive voltage and can be moved left or right depending on the voltage polarity. Recent tests of the performance of the ionomers at low temperatures showed that while the response decreases with temperature, a sizeable displacement was still observed at the temperature of -140^{o}C. This displacement decrease can be compensated by increasing the voltage and it is interesting to point out that, at low temperatures, the response reaches saturation at much higher voltage levels. The deflection level and the consumed power for the ionomer films was tested at both room temperature and -100^{o}C and the results are shown in Figures 2 and 3. Tests of the current as a function of voltage response indicate that the resistance rises with the decrease in temperature, which is in contrast to the behavior of metals and conductive materials.

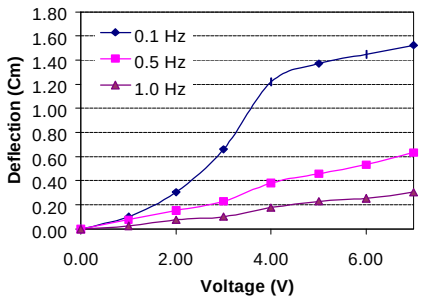


Figure 1: The response of ionomer to various voltage amplitude levels at three different frequencies.

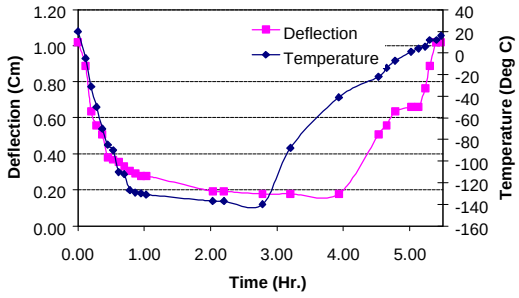


Figure 2: Deflection amplitude of the ionomer as a function of time and temperature.

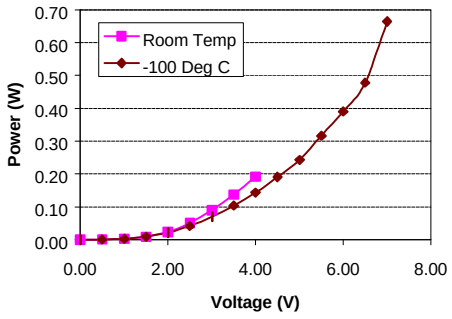


Figure 3: Power consumption of the ionomer bending actuator as a function of activation voltage.

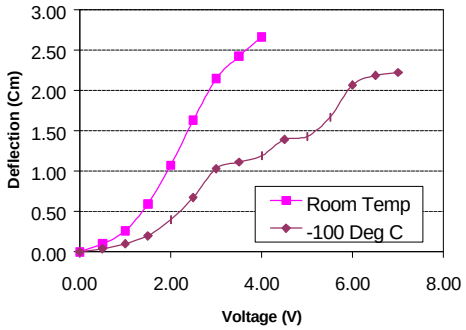


Figure 4: Deflection of the bending ionomer as function of voltage.

Using square wave drive voltages of 1-V and 2-V the curves of the transient I vs. V were determined as shown in Figure 5a and 5b, respectively. The electric current can be seen in Figure 5 to rise simultaneously with the voltage until reaching the maximum level and at the steady state level of the voltage, the current drops to a small value. Further, at the decay stage of the voltage drive the voltage returns to zero and a reversal of the current flow is observed. This behavior indicated the characteristics of a charged capacitor, where the ionomer is charged during the voltage rise time and discharge at the stage of the voltage signal decay time. The decay and rise times of the electric current are lasting several seconds. When activated by the 1-V signal, the charging and discharging currents are shown to have about the same magnitude, with no obvious degradation of the peak current with time. Since the current reaches steady state in several seconds, the ionomer is expected to respond reasonably fast to electro-activation. For a 2-Volt signal, the cycle is seen to have a charging current that is greater than the discharging current. At the rise time stage, the peak current drops to its static value much slower and is showing a larger time constant than the lower voltage case. This behavior indicates that the consumed power is mostly at the rise time stage of activation and if the actuator is held at steady state no power is consumed. Further, upon release of the activation voltage the released power, which is not used for the actuation or heat losses, may be available for reuse. A semi-log plot of the current vs. time does not show a linear relationship with time. This indicates that the ionomer can not be reasonably modeled by using a simple discrete RC circuit. A typical complex impedance plot for the bending muscle is shown in Figure 6. Compared with the semi-circular behavior of the discrete RCs, the complex characteristics of this diagram indicates the need for a distributed parameteric model [Macdonald, 1987]. When the individual ionomer film becomes dried, it was observed that the impedance level rises to level of 8000-Ω and there is virtually no noticeable movement. This change in impedance can provide indication to the wetness status of the ionomer as well as may offer the potential to serve as a sensor for wetness or possibility humidity. Various approaches have been tested to protect the ionomer effectively and to form the equivalent of skin. It is found that an ionomer actuator with a thicker platinum electroding maintains cyclic movement over several hours as opposed to a fraction of an hour for the unprotected ionomer.

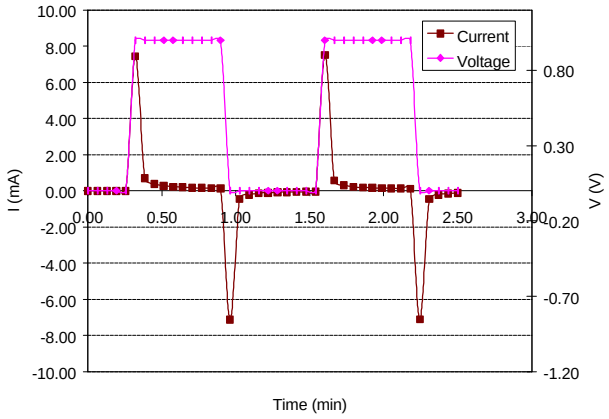


Figure 5a: Current as function of time response to 1-V square wave activation.

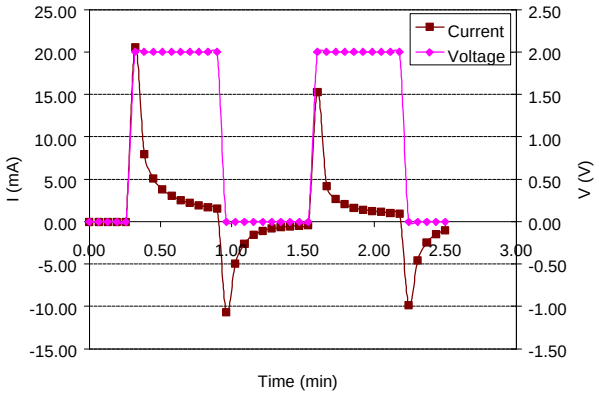
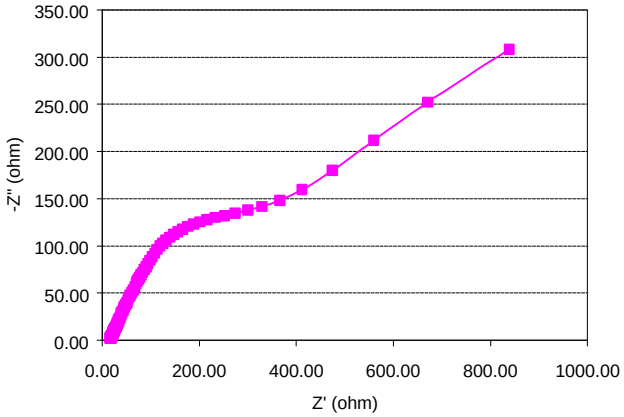


Figure 5b: The effect of increasing the activation voltage of the square wave to 2-Volts.

Figure 6: The complex impedance plane (imaginary vs. real components) for a swept voltage in the frequency range from 1mHz to 200Hz for an ionomer at room temperature. (Vdc=0 and Vac=3V).



3. LONGITUDINAL ELECTROSTATIC POLYMER ACTUATORS

While the ionomer shows a significant level of bending actuation and flexibility, it has very little lifting capability. To obtain a lifting capability with EAP materials, it is preferable to use longitudinal EAP actuators that are made of polymers with low elastic stiffness and high dielectric constant and subjecting it to an electrostatic field. These characteristics of the longitudinal EAP allows producing actuators that operate similar to biological muscles using Coulomb forces between electrodes to squeeze or stretch the material. Traditional electrostatic actuators are fabricated in the form of capacitors with parallel electrodes with a thin air gap between them. One of the major disadvantages of this type of actuators is their relatively low breakdown voltage. The authors adopted the approach that was reported by Kornslush, et al, 1995, where a longitudinal electrostatic actuator was made of dielectric elastomer film coated with carbon electrodes. The candidate materials for such actuators are two polymers that were reported to produce large displacements under electoactivation and they include polyurethane and the silicone. In this study, Dow Corning Sylgard 186 silicone elastomer was used since it offer a large displacement actuation due to its low elastic module and its high dielectric strength. The force (stress) that is exerted normally on such a film with compliant electrodes is as follows:

$$P = \epsilon\epsilon_0 E^2 = \epsilon\epsilon_0 (V / t)^2 \quad (1)$$

Where: P is the normal stress, ϵ_0 is the permittivity of vacuum and ϵ is the relative permittivity (dielectric constant) of the material, E is the electric field across the thickness of the film, V is the voltage applied across the film and t is the thickness of the film.

Examining the equation above, it is easy to notice that the force magnitude is twice as large as that for the case of rigid parallel electrodes. To obtain the thickness strain the force needs to be divided by the elastic modulus of the film. Use of polymers with high dielectric constants and application of high electric fields induces large forces and strains. To obtain the required electric field levels one needs to either use high voltage and/or employ thin films. For elastomers with low elastic modulus, it is reasonable to assume a Poisson's ratio of 0.5. This means that the volume of the polymer is kept constant while the film is deformed under the applied field. As a result, the film is squeezed in the thickness direction causing expansion in the transverse plane. For a pair of electrodes with circular shape, the diameter and thickness changes can be determined using the following relation, where the second order components are neglected.

$$\Delta D / D_0 = (1/2)\Delta t / t_0 \quad (2)$$

Where: D_0 is the original diameter of the electrodes and ΔD is the resultant diameter change, t_0 is the original thickness and Δt is its change under electric activation.

The key to an effective application of the longitudinal EAP is the use of films with a uniform thickness. Since defects such as dust particles, air bubbles, etc, detrimentally affect the functionality of the actuator it is essential to process the EAP films in clean room conditions. Use of thin films allows the effective activation at lower voltages and it increases the level of the breakdown electric field. Various forms of useful mechanisms and structures based on such films include the fabrication of laminated multilayer stacks and scrolled ropes. To produce a longitudinal actuator with large actuation force, a stack of two silicone layers was used with carbon electrodes on both sides of one of the layers. The displacement in the rope cross section is a rotational one around the rope axis and it is constrained by interlaminar stresses. The total actuation extension of the rope is proportional to its length and the resultant actuation force is proportional to the cross-section area normal to the axis. To develop an EAP muscle using a scrolled rope, the length and diameter are used as design parameters, enabling the adaptation of the rope actuator to specific applications. A view of a scrolled rope that is lifting a rock is shown in Figure 7.

Figure 7: View of a scrolled rope

4. CONCLUSION

Two types of electroactive polymer actuators were studied to obtain a large displacement actuation. While the material performance is being enhanced, methods of controlling the actuation performance are being investigated. IMPC are offering a large bending actuation and allow emulating the dexterity of human hand using lightweight material that consumes low power and are inexpensive to produce. For longitudinal displacement actuation, electrostatically activated films were scrolled to form ropes and to serve equivalently to biological muscles. These electroactive polymers are showing a superior actuation displacement, mass, cost, power consumption and fatigue characteristics over conventional electromagnetic, EACs and SMAs. While the force actuation capability of EAPs is limited, their actuation displacement

levels are unmatched. Currently, the practical application of IMPCs is constrained by the need to maintain the ionic constituents and preventing the films from drying. The equivalent of producing a biological skin is being investigated to protect the ion content of IMPC films. Encapsulation techniques are also being investigated to preserve the moisture containment and so far success was observed when using thicker platinum electrodes and voltage levels below 2-volts.

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